IECEC 2002 Paper No.

HUBBLE SPACE TELESCOPE ON-ORBIT NiH_2 BATTERY PERFORMANCE

Stanley J. Krol Jr.
Hubble Space Telescope, Electrical Power Subsystem
Lockheed Martin Technical Operations
7474 Greenway Center Drive, Suite 200
Greenbelt, Maryland 20770
Phone: 301-910-6101, E-Mail: skrol@hst.nasa.gov

Gopalakrishna M. Rao
NASA/Goddard Space Flight Center
Code 563
Greenbelt, MD 20771
Phone: 301-286-6654 E-Mail: grao@pop700.gsfc.nasa.gov

ABSTRACT

This paper summarizes the Hubble Space Telescope (HST) nickel-hydrogen (NiH_2) battery performance from launch to the present time. Over the life of HST vehicle configuration, charge system degradation and failures together with thermal design limitations have had a significant effect on the capacity of the HST batteries. Changes made to the charge system configuration in order to protect against power system failures and to maintain battery thermal stability resulted in undercharging of the batteries. This undercharging resulted in decreased usable battery capacity as well as battery cell voltage/capacity divergence. This cell divergence was made evident during on-orbit battery capacity measurements by a relatively shallow slope of the discharge curve following the discharge knee. Early efforts to improve the battery performance have been successful. On-orbit capacity measurement data indicates increases in the usable battery capacity of all six batteries as well as improvements in the battery cell voltage / capacity divergence. Additional measures have been implemented to improve battery performance, however, failures within the HST Power Control Unit (PCU) have prevented verification of battery status. As this PCU fault prevents the execution of on-orbit capacity testing, the HST Project has based the battery capacity on trends, which utilizes previous on-orbit battery capacity test data, for science mission and servicing mission planning. The Servicing Mission 3B (SM-3B) in March 2002 replaced the faulty PCU. Following the servicing mission, on-orbit capacity test resumed. A summary of battery performance is reviewed since launch in this paper.

INTRODUCTION

The Hubble Space Telescope is a one-of-a-kind spacecraft that pushes technology to its limits. Housing an 8-foot (2.4 meter) mirror and several sophisticated cameras and detectors, the telescope is the largest orbital astronomy observatory ever placed in space. HST was launched aboard the Space Shuttle Columbia on April 24 and deployed on April 25, 1990.

At the time of release on orbit, the calculated pressure based capacity was 67.1 Ah / battery. Early capacity testing resulted between 85.6 and 94.2 Ah. Subsequent battery capacity tests have indicated a declining trend in the battery capacity. This decline in battery capacity has been influenced by the ability to maximize battery charging. HST has endured several power system anomalies and thermal issues, which have limited this ability.

One such anomaly, bus bar impedance in the Power Control Unit (PCU), created a load-share imbalance among the batteries. This anomaly also prevented the execution of battery capacity tests. Consequently, for purposes of mission planning and setting of safe mode triggers, the battery capacity was based on a projection that utilized a linear trend of previously measured capacities.

The PCU was successfully replaced with the flight spare unit, PCUR (PCU Replacement) in the Servicing Mission 3B (SM-3B) in March of 2002. The serviceability of HST and the development of new flight software have been instrumental in regaining and providing new capabilities to overcome some of the battery charging limitations; hence a reduction in the rate of battery capacity degradation.

ELECTRICAL POWER SYSTEM (EPS)

Battery Design

HST EPS consists of a six-battery (6) system (Refs. 1 and 2). The batteries are divided into two (2) modules (Fig. 1) each containing three (3) 88 Ah batteries that were manufactured by Eagle Pitcher Technologies, LLC. (EPT) and Lockheed Martin Missile Space Operations (LMMSO). Each battery has 23 cells; however, only 22 cells are electrically connected in series.

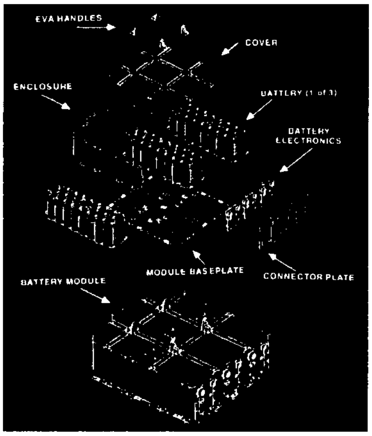

Fig. 1. HST Battery Module

The battery cells are manufactured utilizing dry sintered nickel positive electrodes stacked with the platinum negative electrodes, zirconium oxide cloth separators and gas screens on a polysulfone core. The cell positive plates were fabricated in 1988. The Cells were activated in early 1989.

Each battery has the following dedicated monitors and controls:

- 1 Temperature Monitor for Telemetry
- 4 Charge Control Thermistors
- 1 Primary and One Backup Heater System With Controllers
- 1 Current Monitor (-25 to +25 Amps)
- 2 Cell Pressure Monitors (0 to 1500 PSI), one telemetered through the Data Interface Unit (DIU) A side, the other through the DIU B side, however, only one pressure monitor is read at a time.

The Flight Spare Module (FSM) and Flight Module 2 (FM2) were installed on HST spacecraft. Flight Module 1 (FM1) is in storage at EPT.

Charge System

The HST EPS consists of hardware and software controlled charging modes. The Hardware Charge Control (HWCC) utilizes six Charge Current Controllers (CCC) to manage the charging for each battery (Fig.2). Each CCC provides temperature-compensated multilevel voltage control of battery charging. The CCC, combined with the Voltage Improvement Kits (VIK) installed during Servicing Mission 3A (SM-3A), provide ten temperature-compensated voltage curves for triggering charge termination. The CCCs terminate charge by opening control relays inside the PCU that remove Solar Array Panels (SPA) form the system. The system removes SPAs as batteries reach cut-off voltage. To manage battery thermal, HWCC is configured to remove two SPAs from a battery when it reaches cut-off voltage. Because of the granularity of removing two SPAs at a time, HWCC is susceptible to significant discharge during the trickle charge period.

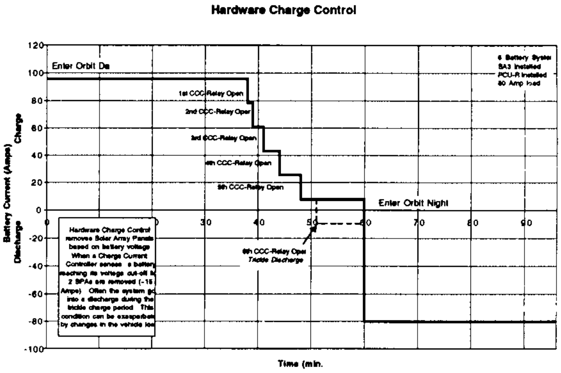

Fig. 2: HWCC Charge Profile

The HST EPS Software Charge Control (SWCC) , also referred to as Trim Relay Software Charge Control (TRSWCC) provides flexibility to specify the number of fully charged batteries to initiate the charge cut-off, tailor the step to trickle profile and manage the trickle charge rate (Fig. 3). Once the specified number of batteries reaches cut-off voltage, the software places the entire system into trickle charge. The flight software commands relays in the PCU, one SPA at a time, to reduce charging down to the specified trickle charge rate. Commanding single SPAs and managing the trickle charge rate greatly reduces the susceptibility to trickle discharge.

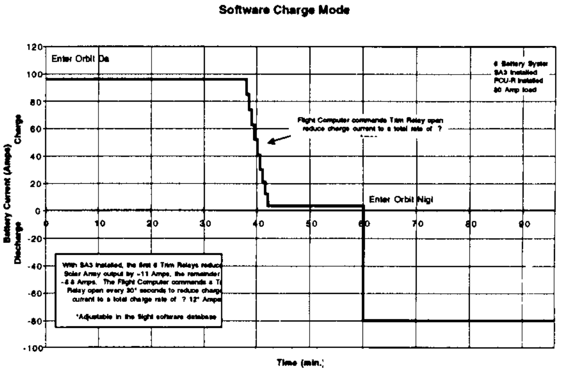

Fig. 3: SWCC Charge Profile

TRSWCC has two modes of operation for triggering battery full charge and trickle charge. The first mode of TRSWCC utilizes the CCCs to sense battery cut-off voltage and is limited to the fixed linear temperature-compensated Voltage (V/T) curves designed into the hardware. A second mode of TRSWCC utilizes a software temperature-compensated Voltage Front End (VTFE) (Fig. 4). The VTFE provides a two-piece linear V/T curve. Each linear section is continuously adjustable in both V/T levels and slope. This mode presently utilizes a steeper slope for battery temperatures above 1 deg C.

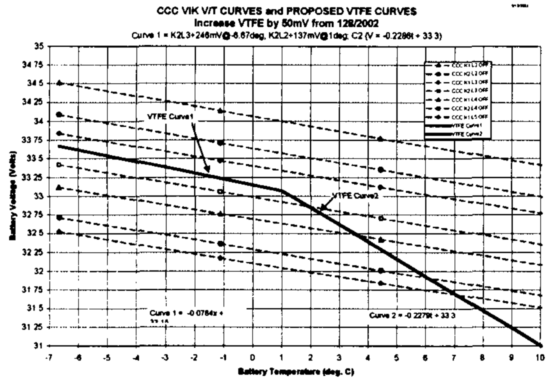

Fig. 4 CCC and VTFE Curves

EPS CONFIGURATION

History

The batteries were charged and installed into the spacecraft prior to HST being transfered to launch pad. This charging conformed to the standard baseline charge used during development and testing of cells and batteries. The charge rates were as follows:

Charge 10 Hours @ 9 amp rate (~C/10)
Charge 14 Hours @ 4 amp rate (~C/24)

HST experienced a launch delay that necessitated removal of the batteries for reconditioning and recharge. At the time of release into orbit, the calculated pressure-based capacity was 61.7Ah / battery.

HST EPS operated in TRSWCC at voltage cut-off levels of "K1 – Level 3, K2- Level 3" from launch in April 1990 until December 1993 when the charge mode was transferred to HWCC after a second SPA Trim Relay failure in the PCU. The charge cut-off levels of K1 – Level 3, K2 - Level 3 proved to be too high for the heat dissipation capabilities of the battery bays and were reduced to K1 – Level 4, K2 – Level 3.

At these levels and in this charge mode, however, battery capacity began to decrease at a rate of 4.8 Ah / bat / year. In an attempt to improve battery charging and charge efficiency, the primary battery heaters were disabled. Disabling the primary heaters, thus relying on redundant battery heaters, allows the batteries to operate in a temperature range of –5 to 0 deg C vs. 0 to 5 deg C with primary heaters enabled. A step increase in the battery capacity was observed following this action.

During Servicing Mission 2 (SM-2) in February of 1997, an additional SPA Trim relay failed. Following this failure, trickle discharge frequency increased from and occasional event to an average of one orbit in five with discharge rates of 5 A / battery. Battery capacity test data indicated a declining capacity trend.

In January 1999, the PCU bus fault rendered battery capacity testing too risky. Batteries 5 and 6 accepted slightly increased charge while serving less of the vehicle load. One SPA was maintained off-line to manage battery 5 and 6 thermal issues due to over-charging.

Just prior to SM-3A in December 1999, the CCC "K61 – relay" failed open resulting in a loss of two SPAs.

During SM-3A the PCU bus fault went into remission and stayed in remission until July 2000. The absence of the PCU bus impedance allowed battery capacity testing to resume. A test was preformed on battery 3 in March 2000 and indicated a declining battery capacity of 5.2 Ah for that battery.

In response to the capacity decline, in April 2000, closing a bypass relay around the failed charge control relay mitigated the SA current loss caused by the K61 relay failure. Additionally at that time, EPS was configured to TRSWCC utilizing the VTFE.

Battery capacity testing was to resume but was halted with the return of the PCU bus fault impedance in July 2000. One attempt was made to perform a capacity test in the presence of the PCU bus fault; however, the test had to be terminated due to fluctuations in the fault impedance.

Without the ability to perform battery capacity checks, the system capacity was estimated based on an extrapolated trend of previous capacity test data (Fig. 5). The estimate was then used for the purpose of setting safemode test limits and in the planning of SM-3B.

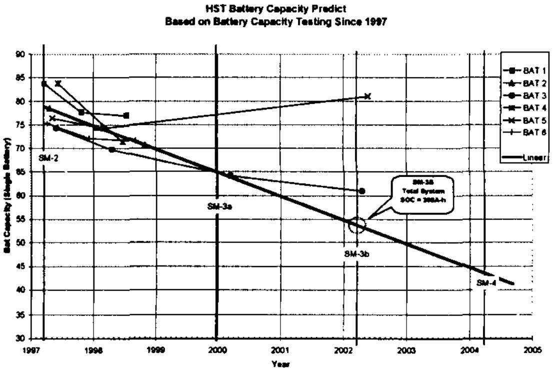

Fig. 5 Battery Capacity Estimating Trend

During SM-3B in March 2002, the faulty PCU was replaced with PCUR and SA2 was replaced with the more powerful SA3. Additionally, Advanced Camera for Survey (ACS) and the NICMOS Cooling System (NCS) were installed. While the PCUR / SA3 configuration does supply 30% more power than the PCU / SA2 configuration for serving the vehicle load and battery charging, the addition of ACS and NCS increase the load demand on the batteries by 35 to 40%. With the PCUR installed, capacity testing became possible.

Following SM-3B, the power system was optimized for the new flight configuration and allowed to stabilize. Battery 3 was the first to be tested in April 2002, as it was the last battery subjected for a capacity check. Battery 5 was next chosen because the influence of the PCU bus fault was still present in that battery 5 (load-share was out of family by approximately plus 6%) which exhibited elevated pressures and was susceptible to heat-up. The results of these tests will be discussed later.

Currently, the HST batteries have performed nominally for 66,445 orbit cycles, equivalent to 12.3 years. With the post SM-3B complement of instruments, the depth of discharge varies between 6 and 9% and the recharge ratios averaging 1.03. The total system State of Charge (SOC), based on the latest battery 3 and 5 capacity tests and the estimates for the remaining four batteries, is about 323 Ah.

Capacity check Method

Battery capacity check is used to determine the actual battery capacity for trend analysis and mission planning. The testing provides data to assess battery health and provides a means of recalibrating the capacity-pressure equations. The deep discharge performed in the capacity test tends to reduce pressure, increase the voltage, improve efficiency and restore cell balance at least for a short period; hence, extend the mission life.

In preparation for a capacity check, attempts are made to normalize test conditions to previous test of the specified battery. Tests are performed with sun-to-orbit ratio (within ±2 minutes), SA / sun incidence angle (±10°) and verify that "trickle discharge" was not present in the orbit day prior to removing the SA section. Other preparations include scheduling TDRSS support to configure, initiate, monitor and reconfigure HST for the test. Forward links are schedule, at least one 15 min. / orbit, during discharge for contingency test termination. Additionally, the battery capacity tests are to be performed without interruption to science observations.

The battery capacity test is initiated by first removing the three SPAs from the battery applying them directly to the bus, and connecting one of two discharge resistors. These resistors are 50.7 ohms for the low rate discharge and 5.1 ohms for the high rate. Only the high rate resistor has been used for the capacity check to date. The battery remains connected to the spacecraft load as well as the resistor and does contribute to the load in orbit night when the system voltage becomes equal to the battery under test.

The on-board flight computer monitors the battery voltage and temperature. When the tested battery discharges to a voltage of 15 V, the flight computer autonomously removes the discharge resistor. The flight computer will also remove the resistor if HST enters safe mode; the battery voltage increases to 33.5 V, battery temperature increases to 7° C or decreases to −8° C.

Following the discharge, battery data is extracted and the discharge current is integrated to determine the Ah removed from the battery as the voltage decreases to the HST equipment minimum usable 26.4 V. The data is then used to recalibrate the pressure based battery capacity equations. These equations are used in performance trending and are applied to various battery models for performing analysis and simulation.

Capacity check data

In December 1990, batteries 1 and 4 capacities were 94 and 93 Ah, respectively. Due to the required long period to charge the battery to a full capacity (pressure), testing was delayed until August 1992. The capacities of batteries 2, 3, 5 and 6 in 1992 were in the range of 88 and 94 Ah. Because of the total system capacity of all the 6 batteries decreased by 90Ah due to the back-to-back testing of the four batteries, the capacity check was placed on hold.

The capacity check was resumed in August 1994. In the time between the 1992 and the 1994 tests, HST EPS charge mode was also changed to HWCC as described above. Additionally, the testing of battery 4 was discontinued due to a relay failure in the PCU that damaged the Data Interface Unit (DIU). In 1994, the capacities of batteries 1, 2, 3, 5 and 6 ranged between 73.5 and 80.4 Ah. In 1995, the capacities of these batteries were ranged between 70.5 and 74.5 Ah. Obviously, the battery capacity was declining by an average of 4.8 Ah / battery / year.

After the primary battery heaters were disabled in November 1995, the tests indicated an increased capacity as expected. In 1996 and early 1997, the capacities of batteries 1, 2, 3, 5 and 6 were ranged between 73.7 and 83.7 Ah. During SM-2 in February 1997, over-voltage protection was added to the DIU to mitigate the risk of additional relay failures and had the added benefit of allowing the capacity check of battery 4 to continue. When battery 4 was tested in June 1997, the capacity was 83.7 Ah compared with the capacity data of 93.4 Ah in 1991. In the late 1997, the capacity of the batteries excluding battery 4 showed further decline with the test data ranging between 72.1 and 76.4 Ah.

HST suffered an additional SPA relay failure during SM-2 that reduced the SA output to the bus by 7.5 A. The loss of this SPA resulted in more frequent and deeper trickle discharge. While initial capacity tests indicated a step increase in capacity following the primary heater disable and SM-2, subsequent tests showed a decreasing capacity trend of approximately 5 Ah / year / battery as seen in tests conducted between June 1997 and November 1998.

In January 1999, a fault developed within the PCU that placed a 25 mOhms impedance between batteries 5 and 6, their respective SA sections and the spacecraft bus. The presence of the impedance resulted in reduced battery 5 and 6 load-share and increased available charge current. Battery capacity checks were discontinued until after SM-3A.

Just prior to SM-3A, EPS suffered a CCC relay failure that reduced the SA output by 15 A. During SM-3A, the PCU bus impedance returned to normal. Capacity testing was resumed with battery 3 in March 2000. Battery 3 capacity was 64.2 Ah compared with the capacity data of 69.8 Ah in April 1998.

The CCC relay failure was indicative of relay wear-out as the CCC relays were exceeding 30,000 cycles. Efforts were then focused on improving battery charging and shifting the cycling of relays to the SPA Trim Relays. In April 2000, we implemented the TRSWCC with the VTFE and mitigated the failed CCC relay failure by closing a CCC / Trim Bypass relay.

The PCU bus fault impedance resurfaced to 25 mOhms in July 2000. In November 2000, a capacity check of battery 1 was attempted. Subsequently, the capacity check was terminated due to fluctuations in the PCU bus impedance.

From this point to until the PCU was replaced during SM-3B in March 2002, the battery system capacity was based on a linear fit extrapolation of recent capacity test data. The extrapolation was necessary for the purpose of setting safemode test thresholds and for SM-3B planning. Based on the extrapolation, in May 2001, the six-battery system capacity was estimated to be 355 Ah. In January 2002, just prior to SM-3B, the system was reestimated and adjusted for a six-battery system capacity of 308 Ah.

With the new PCUR installed, battery capacity testing resumed in April 2002. Battery 3 capacity was 60.9 Ah. Battery 5 capacity was then checked in May 2002. The capacity of battery 5 was 81 Ah. The pressure telemetry suggested 72 Ah capacity in battery 5 after 8 weeks of charge/discharge cycles since the last capacity check. Based on these data, the estimated six-battery system capacity now is 323 Ah and will be reestimated as the additional battery capacity checks will be performed.

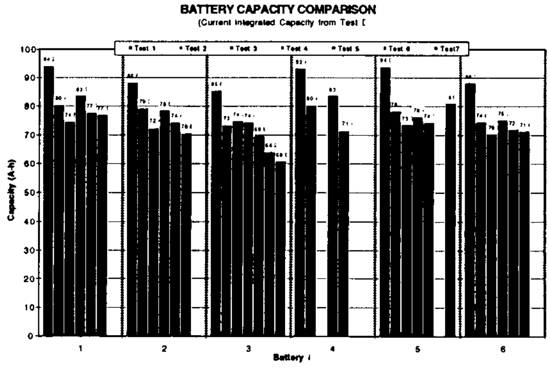

Fig. 6 Battery Capacity Test Results

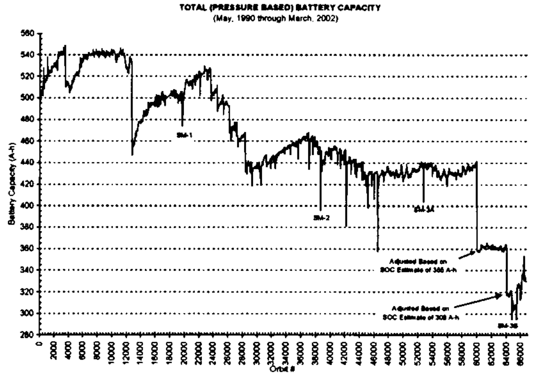

Fig. 7 Calculated Battery Capacity Based on Pressure

CONCLUSIONS

Over the 148 months HST has been in orbit, vehicle configuration, charge system degradation and failures together with thermal design limitations have had a significant effect on the ability to optimally charge the NiH_2 batteries. As a result, battery capacity, as measured during deep discharge capacity tests, has been influenced by the charge capability. Changes made to the charge system configuration in order to protect against power system failures and to maintain battery thermal stability resulted in undercharging of the batteries. This undercharging resulted in decreased usable battery capacity as well as battery cell voltage/capacity divergence.

Efforts to improve the battery performance have been successful. After the primary battery heaters were disabled, the capacity checks indicated an increased capacity as expected. The replacement of the faulty PCU during Servicing Mission - 3B restored capability to the EPS system and has allowed further charge system improvements. As a result, post SM-3B on-orbit capacity measurement data indicates increases in the usable battery capacity in the two batteries tested at this time.

The servicing Mission SM 4 to bring replacement batteries to HST, and to extend HST mission until year 2010 (the deployment of Next Generation Space Telescope (NGST)) is scheduled in year 2004. A decision to replace the batteries will be made after additional HST orbital capacity measurements have been made in 2002, and the data has been analyzed, together with other extended LEO cycling and destructive physical analysis of the extensively cycled cells.

REFERENCES

1. D. Standlee, December 4-6, 1990, "The Hubble Space Telescope Battery background" *The 1990 NASA Aerospace Battery Workshop, p-691.*
2. 1.J. D. Dunlop, G. M. Rao and T. Y. Yi, September 1993, "NASA Handbook for Nickel-Hydrogen Batteries", *p-1-64.*